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OPTICAL NAVIGATION DURING CASSINI'S SOLSTICE MISSION

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After nearly twenty years in flight, Cassini's mission at Saturn will conclude as it purposely dives into Saturn's atmosphere on September 15, 2017. Primarily to avoid moons potentially harboring conditions for life and with propellant very low, the intentional plunge into the atmosphere was set in motion years ago. We take this opportunity to give an overview of the optical navigation and its roles throughout the mission. The paper describes the navigation process and the evolution of optical navigation over the past thirteen years. The last equatorial phase of the Cassini mission was particularly challenging for the OD team as the Saturn system was not being estimated anymore, and it had been a few years since the last icy moon flybys. Science pictures of Enceladus one month prior to the Enceladus encounters confirmed the moon's position to be in good agreement with the Saturn system dynamical modeling used. This reduced Enceladus's absolute uncertainty by a factor of three, less than 1 km, and gave confidence the navigation team could achieve acceptable flybys and meet science objectives.

CASSINI MISSION OVERVIEW

Launched from the Kennedy Space Center in October 1997, the combined Cassini–Huygens spacecraft performed its Saturn Orbit Insertion (SOI) maneuver at the end of June 2004, completing the seven-year interplanetary cruise phase of its mission. Six months after SOI in December 2004, the Huygens probe was deployed and successfully landed on Saturn's largest moon, Titan. The spacecraft's initial four-year Prime Mission at Saturn wrapped up in Sept 2008, culminating with forty-six flybys of Titan and several flybys of the smaller icy moons.

NASA has extended Cassini's mission at Saturn twice. The initial extension for two years is known as the Equinox Mission. During this phase, sunlight transitioned from the southern hemisphere to the northern hemisphere on August 11, 2009, when sunlight was edge-on to the ring plane and Saturn's equator. Vertical ring structure was dramatically revealed by its long shadow cast across the ring plane. Culminating in September 2010, this two-year phase tallied twenty-seven Titan flybys, seven Enceladus flybys, and one flyby each of Rhea and Dione.

An equinox at Saturn occurs every fifteen years, but a summer solstice in the northern hemisphere occurs only once in nearly thirty years. Hence the namesake of Cassini's second extended mission, the Solstice Mission. A seven-year extension of the mission was devised not only to capture the

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highest illumination of the sun on Saturn's north pole but also to capture the gradual illumination of the northern hemispheres of all the moons as well. The summer solstice in the northern hemisphere occurred on May 24, 2017 and since Cassini arrived at Saturn just after the winter solstice in the northern hemisphere, Cassini has been able to observe seasonal changes at Saturn spanning half of Saturn's nearly thirty-year trek around the sun.

Cassini's navigation success is due in part to the many optical navigation images (opnavs) obtained during the mission. This paper tells the evolution of the use of opnavs throughout the mission, from being mission enabling in the first years to reduce uncertainties in the moons' orbits, to maintaining those uncertainties in the second half of the mission. Although details are provided about the entire mission for contrast, the paper provides emphasis on more recent events in the Solstice Mission.

Table 1 summarizes the mission's flyby events after Saturn Orbit Insertion and reflects the added focus to study the intriguing moon Enceladus in the Equinox and Solstice extended mission phases.

Table 1: Targeted Flyby Totals by Mission Phase

Tour Phase	Duration	Titan Flybys	Enceladus Flybys	Other Flybys	Total Flybys
Prime Mission	July 2004 – Sept 2008	46	4	4*	**54**
Equinox Mission	Sept 2008 – Sept 2010	27	7	2†	**36**
Solstice Mission	Sept 2010 – Sept 2017	54	11	5‡	**70**
	Total	**127**	**22**	**11**	**160**

* Hyperion (1), Dione (1), Rhea (1), and Iapetus (1)
† Dione (1), Rhea (1)
‡ Dione (3), Rhea (2)

OPNAV AND CAMERA OVERVIEW

Optical navigation,[1,2] the use of onboard imaging for spacecraft navigation, was part of Cassini's navigation strategy from the beginning.[3] Each of the "opnav" pictures was planned to include at least one of Saturn's principal satellites (Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus, or Phoebe) and at least two sufficiently bright, catalogued stars*. The stars provide the inertial attitude of the camera boresight, allowing the determination of the inertial direction from the spacecraft to the satellite (corrected for light time) at the time of the picture. This is the same strategy used by Voyager and Galileo.

Cassini's narrow-angle camera (NAC) provided almost all of the optical navigation images, because of its higher resolution. With a focal length of 2000 mm and a detector comprising 1024 $\times$1024 pixels 12 μm square, it produced a field of view of 6.14 mrad (0.352) on a side at a resolution of 6 μrad (1.2) per pixel. Note that Cassini also carried a wide-angle camera (WAC), with the same detector but a focal length 10 times shorter, but its only use for opnav purposes was to image the Huygens probe shortly after its release. The cameras were fixed to the spacecraft bus, with the field of view along the spacecraft $-$Y axis. Consequently we had to rotate the entire spacecraft to point the camera at each opnav target. The roll angle about the camera boresight was constrained only by the requirement to keep sunlight from hitting the instrument radiators on the +X side of the spacecraft. In practice, we would use the same secondary axis as for neighboring observations,

*Cassini uses a merger of the UCAC2 and Tycho-2 star catalogs but with parallax information from Hipparcos.

to minimize the amount of turning required. Figure 1 shows the location of the cameras (aka: ISS NAC/WAC Telescope) and their orientation with respect to the Cassini spacecraft. Table 2 shows a listing of each camera's characteristics.

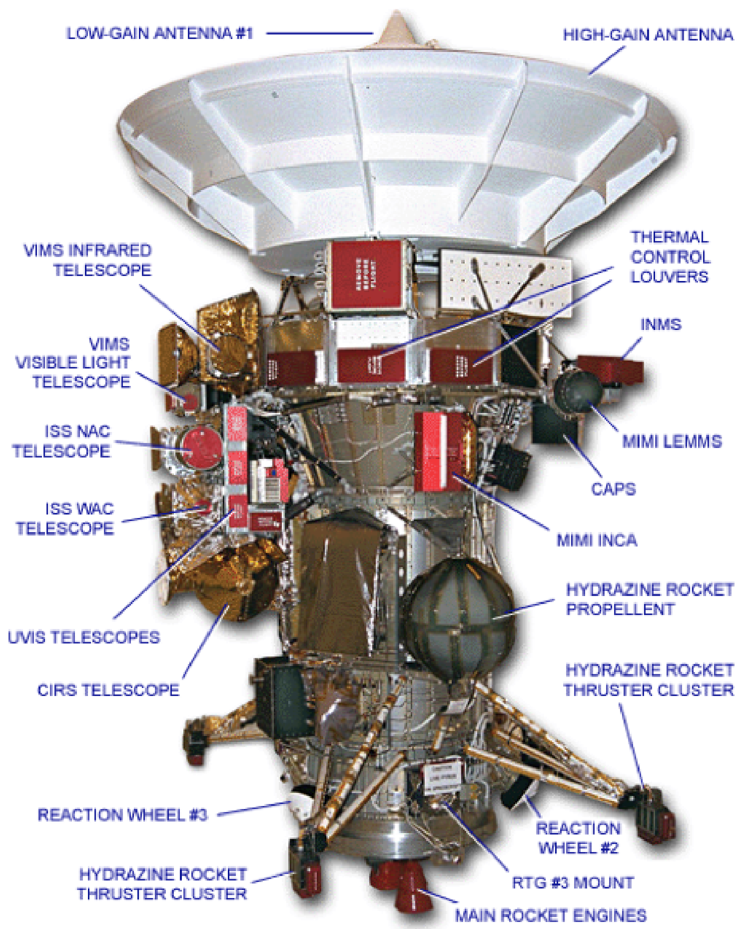


Figure 1: Cassini Spacecraft. *Credit: NASA JPL.*

Both cameras were calibrated before arrival at Saturn and several times thereafter.[4] Pictures of a dense star cluster provided the geometric calibration. As the angular size of a pixel is the ratio of the pixel's physical size to the focal length of the camera, it is impossible to solve for both quantities simultaneously. We therefore held the horizontal dimension of a pixel constant at its nominal value of 12 μm. Solving for the camera focal length provided the angular scale in the horizontal or X direction, and solving for the vertical dimension of a pixel provided the angular scale in the Y direction. We can also solve for an off-diagonal term that would cause the pixel X- and Y-axes to depart from orthogonality, but this term proved not to be significant and was eliminated from the model. We also estimated three distortion terms: one models cubic radial distortion, and two "tip-tilt" terms allow the detector not to be strictly perpendicular to the optical axis. These were found to amount to a total of 0.25 pixel in the corners of the narrow-angle field and 1.2 pixels in the corners of the wide-angle field. The distortion coefficients did not change significantly during the mission.

Table 2: Cassini NAC and WAC Characteristics

NARROW-ANGLE CAMERA

Parameter	Value	Sigma
Focal length (mm)	2002.703	0.017
Pixel width (μm)	12.0	(assumed)
Pixel height (μm)	11.99863	0.00015
Cubic radial distortion (mm^{-2})	8.28E-6	0.06E-6
Tip/tilt in x (mm^{-1})	5.45E-6	0.34E-6
Tip/tilt in y (mm^{-1})	-19.67E-6	0.30E-6

WIDE-ANGLE CAMERA

Parameter	Value	Sigma
Focal length (mm)	200.7761	0.0061
Pixel width (μm)	12.0	(assumed)
Pixel height (μm)	11.99888	0.00045
Cubic radial distortion (mm^{-2})	60.88E-6	0.16E-6
Tip/tilt in x (mm^{-1})	5.28E-6	0.61E-6
Tip/tilt in y (mm^{-1})	-71.86E-6	0.61E-6

INCORPORATING THE OPNAVS

Optical navigation images of Saturn's satellites against a background of known stars greatly augmented the radiometric Doppler and range data from NASA's Deep Space Network in Cassini's orbit determination process for the first few years of the Prime Mission. The opnavs of Saturn's moons were critical in these first few years as there were large uncertainties in their positions prior to Cassini's arrival at Saturn in July 2004. A particularly interesting case was the Phoebe flyby, just before Saturn Orbit Insertion (SOI). Cassini imaged Phoebe nineteen times between May 27 and June 10, 2004. Combined with fifty images of the other moons obtained during the same interval, the opnavs reduced Phoebe's one sigma ephemeris uncertainty from $\pm$1600 km to $\pm$3 km just ahead of a 2000 km flyby of Phoebe, the only targeted flyby of Phoebe in the entire mission. Consequently, Phoebe's time in the spotlight was short lived, as this very distant moon of Saturn had no further opnavs planned for the remainder of the mission.

For most of the first two years of the Prime Mission, eight optical navigation images were planned daily. These were useful not only to help determine Cassini's trajectory but also to improve the ephemeris of the satellites. The rate reduced to approximately three to six images per week from November 2005 to the end of the Prime Mission in July 2008. Opnavs of Titan were less effective in navigating Cassini and were quickly discontinued, because Titan's thick atmosphere limited the accuracy of these measurements. Gravitational modeling during the many close flybys was found to quickly surpass the accuracies obtainable with opnavs. As a result, images of Titan were deemed un-necessary after April 2006, and was afterward included in only four pictures in 2015 when it appeared in the same frame with Dione and Mimas.

By the end of the prime mission, with satellite uncertainties significantly reduced, the optical navigation effort evolved into a background task to prevent runoff errors in the Saturnian satellite orbits from building up over time. The along-track uncertainty of the satellites, in particular, is expected to grow with time without the addition of new data. With a new strategy adopted, the opnav imaging rate reduced to about three or four frames per week on average during the Equinox Mission. Additionally, the five closest moons (Mimas, Enceladus, Tethys, Dione, and Rhea) were deemed a priority due to their shorter orbit periods. See Table 3 for mean radius and period values of Saturn's primary moons. A total of 218 images of the satellites were obtained during the Equinox Mission, with some images capturing more than one moon in the frame.

Table 3: Saturn's Primary Moons

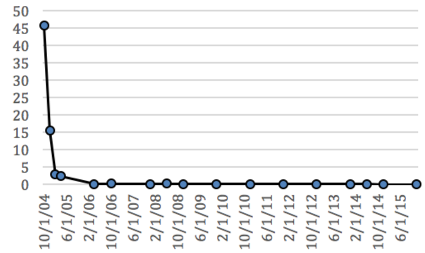
Moon	Mean Radius (km)	Period (days)
Mimas	198.2	0.94
Enceladus	252.1	1.37
Tethys	531.1	1.89
Dione	561.4	2.74
Rhea	763.8	4.52
Titan	2575.5	15.95
Hyperion	135	21.28
Iapetus	734.5	79.32
Phoebe	106.5	550.56

The Solstice Mission saw a drastic reduction in the opnav rate, one picture per revolution of Cassini about Saturn or about one picture per month. Compared to the 2768 images obtained in the previous 6.5 years of the mission (including images taken prior to SOI), only eighty-four opnav images were planned for the last seven years of the mission. Although there were numerous icy moon flybys of great interest scheduled in the Solstice Mission, the radiometric tracking data would be sufficient as the main source of measurements to produce trajectory solutions that would meet project requirements. The final count of usable images of each satellite is given in Table 4.

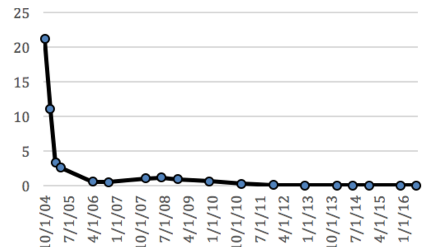
Table 4: Opnavs by Satellite and Mission Phase[5–7]

Satellite	Pre-SOI	Prime	Equinox	Solstice	Total
Mimas	62	301	47	14	**424**
Enceladus	58	317	44	12	**431**
Tethys	57	267	48	12	**384**
Dione	61	286	42	13	**402**
Rhea	67	292	32	14	**405**
Titan	49	119	0	4	**172**
Hyperion	42	196	2	8	**248**
Iapetus	46	189	3	7	**245**
Phoebe	95	46	0	0	**141**
Total	**537**	**2013**	**218**	**84**	**2852**

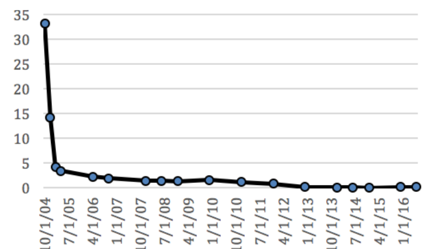
Optical navigation imaging had to compete for observing time on the spacecraft with all twelve of the instrument teams. Because every instrument was immobile, to point any instrument required turning the entire spacecraft. Cassini's science planning team devised a "waypoint" strategy whereby each science observation would begin and end with the spacecraft in a particular safe waypoint attitude. This strategy made each observation independent of its neighbors. Because the opnav engineers worked so closely with the rest of the spacecraft team, we had permission to begin and end our time at two different attitudes: one had the high-gain antenna pointed at the Earth, and the other was the appropriate waypoint. This freedom eliminated turns between the waypoint and Earth point, and by placing opnav pictures on either side of downlinks we interrupted science observations the least.[3]



(a) Titan Position Uncertainty (km)



(b) Enceladus Position Uncertainty (km)



(c) Dione Position Uncertainty (km)

Figure 2: RSS of Position Uncertainty Over Time

Figure 2 depicts the one-sigma position uncertainty of Titan, Enceladus, and Dione over the past twelve years of the mission. Before SOI and the first Titan flyby (Ta), these uncertainties were as high as 182, 465, and 263 km, respectively. They quickly improved after the first few flybys and sets of opnav images. These values were obtained from the various Saturn system ephemerides and associated covariance data delivered by JPL's Solar System Dynamics (SSD) group. As explained in the next section, those satellite deliveries are a product of processing both radiometric measurements and opnavs (including Earth-based images spanning four decades).[8]

NAVIGATION OVERVIEW

The navigation team's primary task is to maintain Cassini's actual trajectory close to its planned reference trajectory. The timing and geometry of targeted flybys are tightly controlled, while allowing some dispersion to occur between flybys. The navigation team was originally divided into four main groups: Orbit Determination (OD), Flight Path Control (maneuver), Opnav, and Trajectory Design & Analysis. Since the Solstice mission began, the Opnav tasks were integrated into the OD tasks.

The OD team tasks are to provide orbit predictions for maintenance of the trajectory and occasional science observation updates and orbit reconstructions for accurate science processing. The OD process includes a refined dynamical model of our solar system, especially the Saturnian system and the Cassini spacecraft. The real-time information is processed to update the many parameters being estimated in calculating the Cassini trajectory and associated uncertainties. Initially, the latest measurements from the Deep Space Network (DSN), including radiometric range (for line of sight position), Doppler (line of sight velocity), and opnavs are appended to our master data sets. We then update ionosphere, troposphere, and Earth orientation calibrations, along with small forces, and other dynamical events (for instance, an orbit trim maneuver, or OTM) in the estimated parameters list. The measurements are then compared to predicted measurements, and the residuals are minimized through a least squares filter, done within JPL's MONTE navigation software used for flight operations.[9] To account for errors on other parameters not estimated, "consider" parameters are also included in the fit. The computed updates are applied to the estimated parameters and the process is iterated until convergence. Figure 3 below depicts the process in a flow chart.

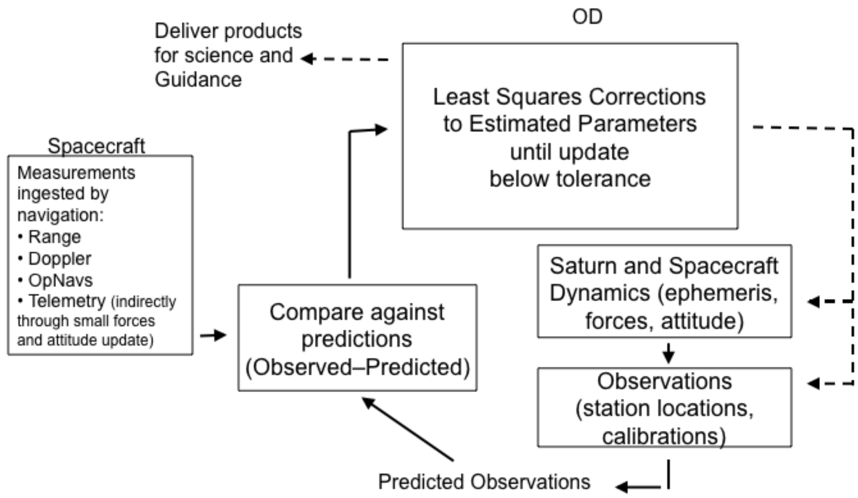


Figure 3: Orbit Determination Process

The opnav process has been well documented by Gillam et al in 2007 (see Reference 3); however, a short description of the process is in order. An overlay of the expected stars' positions and the illuminated portion of the target moon's disk is placed on top of the actual opnav image obtained by the camera. The analyst simply has to drag the overlay over the right spot to line up the brighter stars inside their tiny target boxes from the overlay. Stars are preferred for this initial alignment as the moon is usually considerably over exposed to allow the CCDs to record the much fainter background stars. Care is necessary here as there are many extraneous bright pixels caused by cosmic ray hits or damaged cells. After this first effort, the analyst zooms in on each individual star to better align that star's target box with the brightest pixel in the expected location. Usually the eye is adequate here, but there is a DN (data number) chart available pixel by pixel, to help one select the brightest candidate pixel for each star when occasionally a bright star can saturate a block of four pixels. After the stars are complete, the overall image saturation is greatly reduced to allow the details of the moon to be visible. In a similar manner to the stars, the overlay for the moon is carefully dragged into its best position to encompass the moon's actual image as best as possible. One has to guard against the tendency to bias the overlay in the direction of the illuminated portion of the moon (dependent on the phase angle with the sun), which would be an error. On occasion there was some partial illumination of the dark disk by light reflecting from Saturn's clouds (Saturn-shine). Collectively, the role of the analyst is to act as a pre-processing step to the complex center-finding and limb fitting algorithms within the software that follows, where the 'real' solution is determined.

The Saturn system ephemeris data are obtained from processing both radiometric and opnav data. Over the years, the OD team has used a combination of local and global fits. Local fits are performed by the OD team and are more focused on the last few revs of the spacecraft; whereas global fits, performed by the Solar System Dynamics Group at JPL, are a comprehensive re-fit of all available data. Local fits are available quickly (hours) and global fits require more time (weeks). Toward the end of the Solstice Mission (2014 to 2016), the OD team stopped estimating the Saturn pole, gravity, and satellite ephemerides locally because it became unnecessary. The addition of a few more revs of data did not change the satellite ephemeris significantly when over a hundred revs had already been used to constrain the covariance. While simplifying the operations, the monthly opnavs were not incorporated directly into our daily orbit analysis as they once had been, but periodically updated from the SSD deliveries. As a note in 2016, the OD team resumed estimating the Saturn system for better predictions of the remaining Titan encounters.[10]

LAST EQUATORIAL PHASE AND ICY MOON FLYBYS

In the spring of 2015, toward the end of the Solstice Mission, there was one last equatorial phase of the mission to enable one last survey of Dione and Enceladus. This opportunity involved a low flyby of Enceladus to allow one last dive through its south pole's geysers. The Navigation team and Cassini project both wanted the best possible flyby performance. Figure 4 depicts the orbital inclination changes of Cassini's orbit throughout the Solstice Mission. Note that the two equatorial phases, designated Eq-1 and Eq-2, at nearly zero degrees inclination, are the timespans allocated and best suited for the icy moon flybys. Also, a sampling of the 56 Titan flybys of the Solstice Mission are depicted with the codes T73 to T126. Finally, we note that Figure 4 also depicts the effects of the last twelve Titan flybys of the mission, which slowly crank the orbit inclination up substantially to set the stage for the dramatic mission's end game.

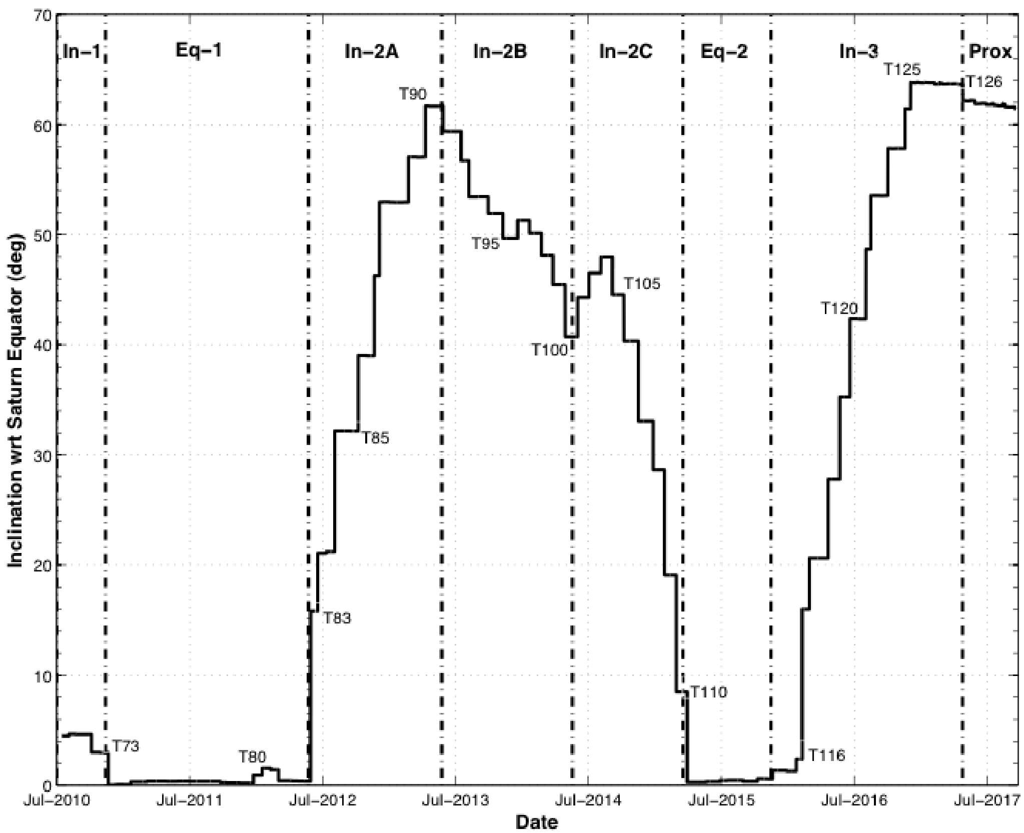


Figure 4: Solstice Mission Inclination versus Saturn Equator (deg). *Source: Cassini Solstice Mission Navigation Plan (Reference 7).*

As can be seen in Figure 4, the previous equatorial phase (Eq-1) spanned all of 2011 to mid-2012, nearly three years prior to the final equatorial phase (Eq-2), which spanned the latter half of 2015. There was concern that the accurate orbit information of the moons gained during Eq-1 would now be slightly stale, due to the slow accumulation of errors in the moons' orbits. More specifically, it's primarily the down-track component of the orbit uncertainty that tends to be the worst, especially with moons that have relatively short orbit periods. Enceladus orbits Saturn every 1.37 days and Dione every 2.74 days. This would mean that Enceladus orbited Saturn nearly 920 times and Dione about 468 times since their last respective Cassini flyby. Having an initial position uncertainty of only 40 meters, spanning that many orbits could mean tens of kilometers in accumulated run-off errors.

During the planning for this seven-year Solstice Mission, we scheduled an opnav image of one of the moons monthly for the primary purpose of keeping these run-off errors in check. During operations, these images were in fact being taken right on schedule and processed by the navigation team in a timely manner. At the time of the processing of these opnavs, all indications were that the predicted locations of the moons were pretty well confirmed, as overlays aligned well with the moons' actual positions. There was some concern, however, that there may not have been enough images of specifically Dione and Enceladus scheduled to keep their uncertainties small, since they were the only two target bodies to be visited in the final equatorial phase (Eq-2) of the mission. Table 5 shows a listing of just the icy moon flybys (non-Titan) of the Solstice Mission.

Table 5: Solstice Mission Icy Moon Targeted Flybys[7]

Moon	Date	Altitude (km)
Enceladus-12	30-Nov-2010	50
Enceladus-13	21-Dec-2010	50
Rhea-3	11-Jan-2011	75
Enceladus-14	01-Oct-2011	100
Enceladus-15	19-Oct-2011	1236
Enceladus-16	06-Nov-2011	500
Dione-3*	12-Dec-2011	100
Enceladus-17	27-Mar-2012	75
Enceladus-18	14-Apr-2012	75
Enceladus-19	02-May-2012	75
Dione-4	16-Jun-2015	517
Dione-5	17-Aug-2015	474
Enceladus-20	14-Oct-2015	1840
Enceladus-21	28-Oct-2015	50
Enceladus-22	19-Dec-2015	5000

* Part of dual flyby w/ targeted Titan-79

The concern was especially directed at Enceladus, as E-21 was to be done at an altitude of 50 km from the surface. Two opnavs were scheduled in May 2015, one each of Dione and Enceladus, just prior to the dual flybys of Dione in June and August 2015. The nominal plan was to obtain an update of the Saturn system parameters and ephemeris after including the two Dione flybys in the overall fit. As Enceladus and Dione are in a 2:1 mean motion resonance (that is, Enceladus makes two orbits for every single orbit of Dione), the addition of Dione's updated information would also improve Enceladus's ephemeris. Leveraging the resonance knowledge facilitates the mission's efforts to maintain the moon's orbits and uncertainties*.

*Mimas and Tethys are in a 2:1 resonance. Titan and Hyperion are in a 4:3 resonance.

In an effort to better quantify the run-off errors of Dione and Enceladus after the opnavs arrived in May 2015, we employed a number of different filter strategies. In particular, two solution strategies were implemented, one estimating the Saturn pole, gravity, and satellite ephemerides, and one where these parameters were only considered. When projecting the trajectory of Cassini and associated uncertainties of both of these solutions onto the upcoming flyby B-plane, the solutions were only two-sigma apart, about 0.5 km. The solution uncertainties are shown in Figure 5, where *150611_satest* and *150611* denotes the solutions with and without estimating the orbits of the satellites. The relatively small difference in the solutions provided some comfort to the navigation team about five months ahead of the fast-approaching low Enceladus flyby.

As noted earlier, JPL's Solar System Dynamics (SSD) group has provided Saturn system ephemerides and associated covariance data updates at regular intervals throughout the mission. Updates were warranted periodically as new icy moon flybys accumulated, naturally extending the data arc as the mission progressed. One particular update, known as sat375, was part of the OD team's nominal baseline process for an extended period of time.

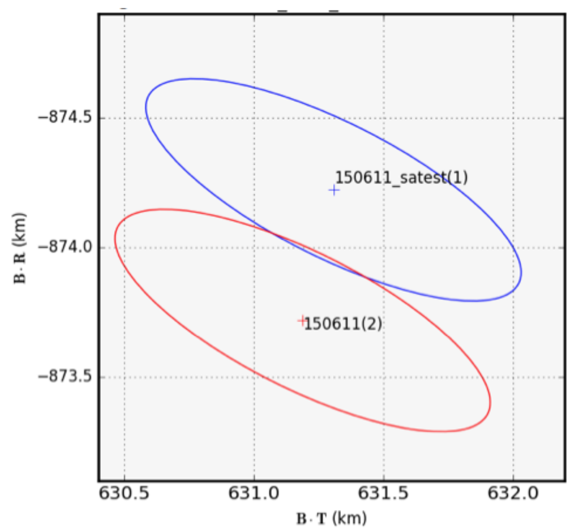
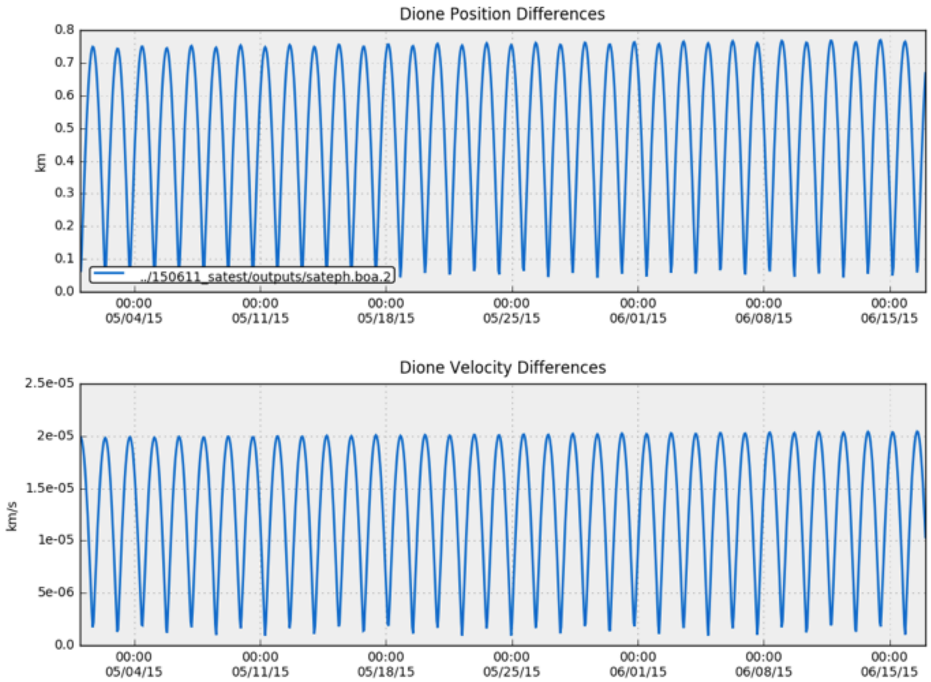


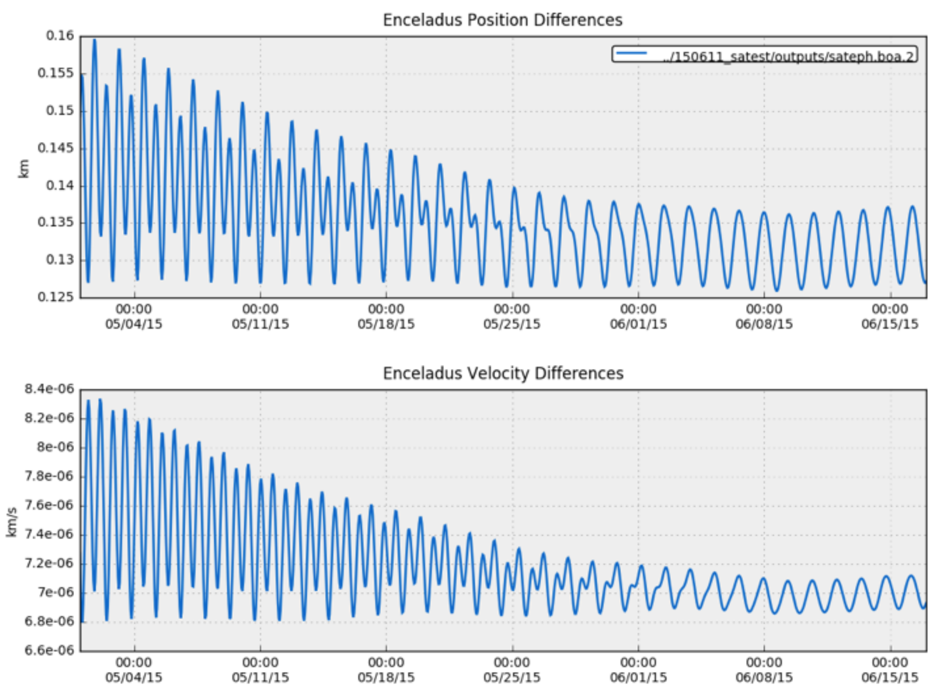
Figure 5: Dione-4 B-Plane on June 16, 2015

Figure 6 compares the effects of the subtle changes to a moon's ephemeris introduced by estimation after a flyby or a recent opnav with respect to the sat375 global fit. Figure 6 shows that the position errors for Dione and Enceladus were less than 1 km and less than 200 m, respectively, during the timespan of the May opnavs and the Dione-4 flyby in mid-June. Figure 6 shows those differences in terms of position and velocity between the 150611_satest ephemeris solution and the baseline sat375 solution with tracking data through June 11, 2015.

However, the Dione-4 and Dione-5 flybys introduced a few difficulties, later found to be due to the moon Helene slightly affecting Dione's orbit and its resonant companion Enceladus. Helene is a small co-orbital moon with Dione and is located in its leading Lagrangian point (L4). Much smaller Polydeuces is Dione's other trojan moon and it resides in the vicinity of the trailing Lagrangian point (L5). Although each moon has a relatively small covariance from the overall Saturnian-system fit, the absolute difference for Dione and Enceladus between some of the satellite ephemeris updates could differ by up to 10 km. Figure 7 gives a comparison between sat375 and two subsequent satellite ephemeris delivered by the SSD group as examples. At the time, these updates caused much confusion as to the actual knowledge of Enceladus. Fortunately, late in September 2015 there were a few science pictures taken of both Dione and Enceladus which confirmed that the errors for these moons were small, on the order of 1–2 km rather than 10 km. Eventually, the OD team was updated with sat389 which agreed well with our local fit, regrettably after all of the Enceladus flybys had completed.

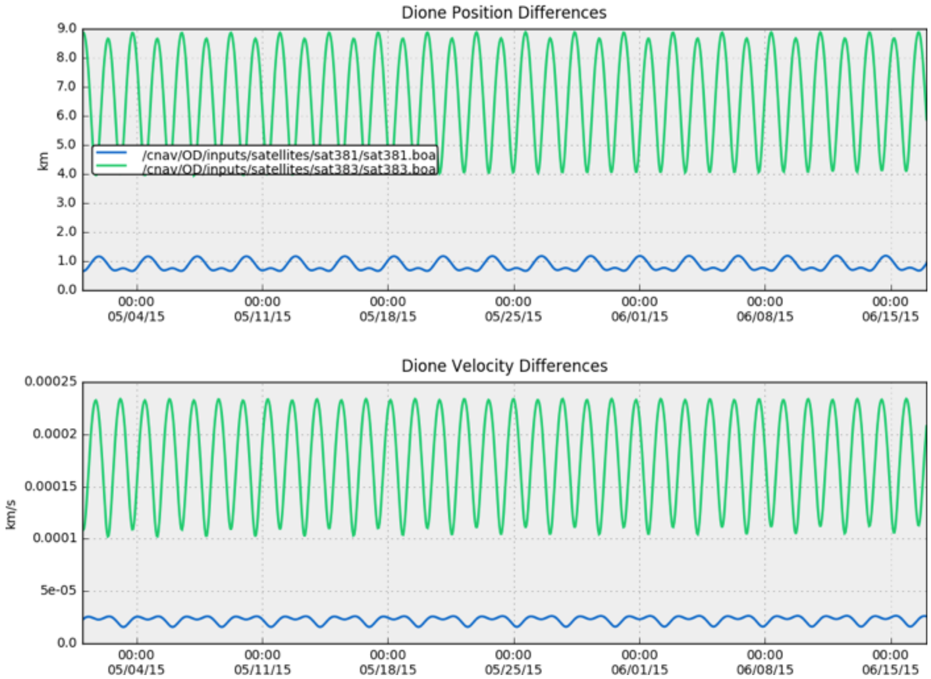


(a) Dione Position and Velocity Differences



(b) Enceladus Position and Velocity Differences

Figure 6: Corrections to Dione and Enceladus Position and Velocity Introduced by Satellite Estimation Relative to sat375 Baseline



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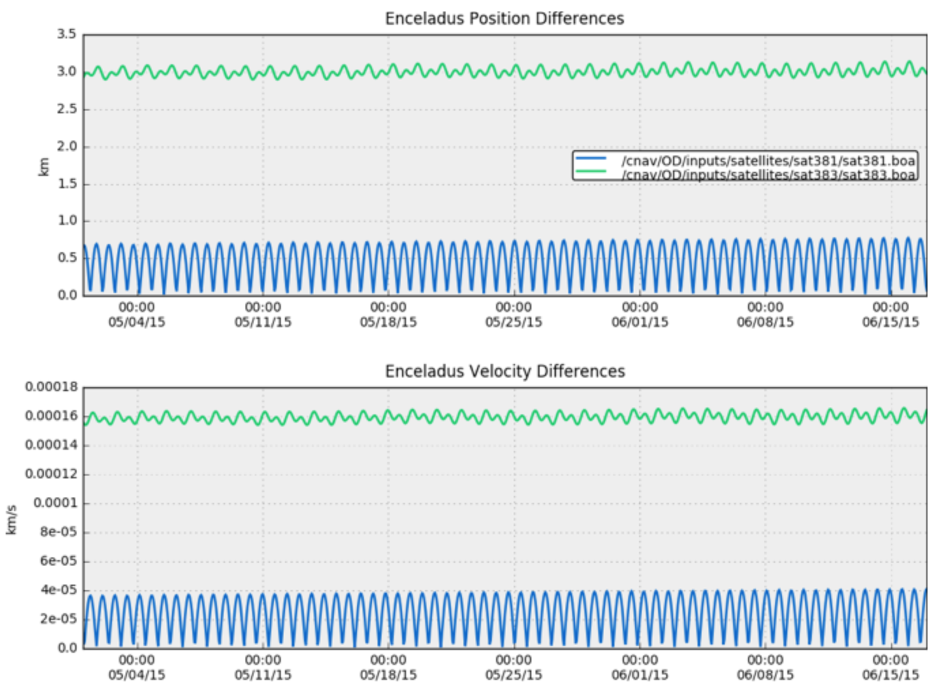

(b) Enceladus Position and Velocity Differences

Figure 7: Variations in Dione and Enceladus Position and Velocity due to Different Ephemeris Deliveries Relative to sat375 Baseline

Table 6 gives the OD performance for the Titan and icy moon flybys in the Eq-2 phase of the mission. Pre- and post-flyby solutions are differenced to provide a 3-D sigma value, while the error vector is projected onto the covariance of the pre-flyby solution to provide a 3-D sigma value. All of the icy moon 3-D flyby errors were found to be less than one km, with the exception of E-20, which was slightly higher at 1.68 km.

Table 6: OD Performance of All Flybys During the Last Equatorial Phase (Eq-2)

Target	Date	Altitude (km)	3-D error (km)	3-D sigma
Dione-4	16-Jun-2015	516	0.74	1.8
Titan-112	07-Jul-2015	10953	0.34	1.4
Dione-5	17-Aug-2015	475	0.42	1.4
Titan-113	28-Sep-2015	1036	0.13	0.7
Enceladus-20	14-Oct-2015	1840	1.68	2.4
Enceladus-21	28-Oct-2015	50	0.91	1.4
Titan-114	13-Nov-2015	11920	1.21	9.9
Enceladus-22	19-Dec-2015	5000	0.14	0.4

CONCLUSIONS

Although there were the normal bumps along the way, the remaining icy moon flybys of the Solstice Mission were successful and did meet project requirements. The methodical scheduling of monthly Opnavs throughout the Solstice Mission provided some reassurance that the moons' uncertainties were small and kept in check. A few timely located science images also contributed to the knowledge that the moons' positions were well known. The opnav images independently validated that ephemeris uncertainties were indeed small and were essential in preparation for the final low flyby of Enceladus of the mission.

In general, opnav images provide a unique data type to the orbit determination process, completely independent of the typical radio metric sources such as the Doppler and range data. Although Cassini navigation did not rely on the opnavs as they had in the earlier mission phases, they did serve the role they intended to provide; keeping the icy moon uncertainties in check prior to their scheduled flybys. Had the navigation team been without opnav images through the Solstice Mission, we probably would have raised the altitude of the 50 km Enceladus flyby (E-21) in late October 2015.

Cassini's nearly 3000 optical navigation images played an important role throughout its mission, not only for their contribution to a lengthy and successful navigation tour, but also for their continued refinement of Saturn and its satellites' ephemerides (Jacobson, personal communication, July 2017). The results obtained will provide the next Saturn missions with a well-defined Saturn system.

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